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(Selected Articles)

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TITLE: SOLID STATE LASERS ENTER A PERIOD OF VIGOROUS DEVELOPMENT--IMPRESSIONS ON A VISIT TO U.S.

AUTHOR: Mei Suisheng

This article reports the author's impressions from a visit to the U.S. in May, 1989. The report describes the rapid development in recent years of solid state laser technology in areas of application such as high average power, semiconductor laser device pumps, tunability, narrow line width, and other similar solid state laser devices, as well as laser materials processing, and so on.

From May 11-26, 1989, a group of three of us visited the U.S. to participate in an investigation. We visited 11 such units as Lawrence Livermore National Laboratories, Stanford University Ginzton Laboratory, Central Florida University Electroptics and Laser Research Center, the Quantronix Company, the Control Laser Company, the Electroptics Division of the Holometrix Company, the Laser Products Division of the Raytheon Company, the Electroptics Divsion of the Honeywell Company, the Laser Products Division of the Spectra Physics Company, the Electroptics Division of the E.G.& G. Company, and the ILC Technology Company. We also participated in the grand scale Semicon/West International Exhibition.

On this visit, we contacted a good number of scholars, specialists, and management personnel, and we saw many types of solid state lasers and complete devices. We visited a number of laboratories and workshops, and obtained a variety of impressions. These impressions, concentrated into one point, are simply that solid state lasers have entered a period of vigorous development.

(I)

Solid state lasers are one of the types of lasers that appeared earliest. Up to now, they have close to 30 years of history. In the first ten years, development was relatively fast. Output energies and powers rose rapidly. New applications appeared constantly. After that, their development drew far less of people's attention than did gas or semiconductor lasers. A good number of people acknowledge that solid laser technology is already familiar, in a fixed form, does not have a large number of new technologies to study, and the main work to it is resolving problems of production and application. In recent years, solid state lasers have ceaselessly developed in such areas as

materials, instrument structures, and pump sources, as well as other similar aspects. The stalmated situation has been completely broken out of, opening up a totally impressive future prospect. On our visit this time, we got wind of several areas of great breakthroughs. These were: high average power high luminosity solid state lasers, solid state lasers with semiconductor laser pumps, wide band tunable solid state or solid lasers, and single longitudinal mode (single frequency) solid lasers. Besides this, there were also new developments in the areas of laser materials and pump lamps. These breakthroughs and developments must necessarily bring deep and far-reaching effects to the applications and production of solid state lasers.

1. High Average Power High Luminosity Solid Lasers

Going through a relatively long period of research, board or plank shaped solid laser devices are just turning from the laboratory to industrial production. The materials used include Nd:YAG crystals, Nd:GGG crystals, and phospate glass mixed with Nd. The Hoya Optics Company's glass "plank" laser has already reached 480W. They are just in the midst of designing a 1500W version(1). [(1) After returning to China, we received this Company's General Manager Mr. Segawa and its Research and Development Department's Director, Dr. Meissner. At that time, we understood that they had discovered a superstrength diffusion binding technique, which is capable of taking two pieces of crystal or two pieces of glass and firmly binding them to form one complete monolithic body. It is possible to make use of this in high power laser devices. For example, it is possible, on the sides of slice shaped laser material, to plate absorbant material in order to prevent the surprise occurence of oscillation, and it is possible to take small pieces of high quality laser material and (illegible) put together large pieces of material, and so on.]
For a long period of time, the Livermore Laboratories have invested huge amounts in the study of high average power solid state lasers, and unstintingly researched new laser operating substances, nonlinear crystal materials, and new instrument structures. Their objective in the near term has been a multiplication frequency power of 200W. In particular, the strength modulation of light bundle quality must be good. They have made "plank" or "strip" laser devices with output

base waves that approach 1kW. However, light bundle qualities are very far off the mark and are still not capable of application. Their long term objective is nuclear fusion being made to be balanced in its input and output with pulse energies reaching 10MJ. In order to cause production costs to drop down to levels which the U.S. Government is capable of accepting, it is necessary to very, very greatly increase the efficiency of the instruments. From now on, within a few years, it is possible that a selection will be made between solid state lasers and KF laser devices. Stanford University is also studying old units associated with "plank" or "strip" laser devices. At the present time, they are involved in studying "plank" or "strip" laser device amplifiers and small model "plank" or "strip" laser devices using semiconductor laser device pumps.

2. Solid State Laser Devices With Semiconductor Laser Pumps

This type of laser device has high efficiency, long life, light weight, and has changed the heavy circulating water cooling system which the original solid state laser devices carried with them as well as the inconvenience of frequently changing lamps. Currently, there are already commercial products on sale. In conjunction with this, these are already used in laser microprocessing devices and a number of complete devices for military use. On the basis of what is said, the ouput light bundle or beam quality is good, and the output power stability is capable of being better than 3%. At the present time, the laboratory levels have already reached the Watt order of magnitude. Stanford University is in the midst of test producing a high power pump using 60 1W semiconductor laser devices. It is predicted that its output is capable of reaching 15-20W. Professor Byer ardently says that, after 2 years, it is capable of reaching 200W! He also has a very optimistic attitude about the selling price of the lasers. It is acknowledged that the selling price of semiconductor lasers using pumps is the same as that of other semiconductor instruments. The numbers of these instruments produced is directly related. He estimates that a few years from now, the selling price of semiconductor devices will plummet 4 fold every year. If, at the present time, each Watt is $1,000 U.S. (This is the prefered price given it by the SONY Company.), in that case, in 1992,

it will then plunge to $10 U.S. for each Watt, and, in 1994, each Watt will be $1 U.S. Despite the fact that this estimate may possibly be excessively optimisitc, this trend, however, is undoubtedly accurate.

3. Wide Band Tunable Solid State Lasers

Last year, the Spectra-Physics Company put out an adulterated titanium sapphire laser. It is tunable within the range 700-1000nm. Its average power reaches 2.5W. In close infrared ranges, it is capable of replacing a large number of applied dye lasers in use at the present time. Another path for the realization of wide band tunability is optical parameter oscillators. In recent years, they, too, have gone through relatively large developments. Stanford University, using BBO crystals, obtained wide band tunable outputs from the optical (400nm) to the infrared ($3\mu m$). This is the first instance, in the visible light wave band, of realizing tunable capabilities. The output power was several milliwatts in a single vertical mode or frequency. However, at the present time, the BBO crystal quality is still unworkable. The whole crystal is filled with inclusions. Using lithium niobiate as a participant in the vibration is also a problem. The double photon absorption is too severe. They use small ring shaped YAG laser devices associated with semiconductor laser device pumps. The output is 57mW. Using lithium niobiate, frequency multiples achieve 24mW. Again, using a different piece of lithium niobiate to act as a participant in the optical vibration, output reaches 8mW. Central Florida University is also in the process of test studying two types of optical parameter oscillators. Tunable lasers are capable of broad uses in physics, chemistry, biology, the science of materials, as well as military applications. The market is exceptionally large. As far as the complete conversion to solid state in tunable lasers is concerned, their structures are compact. They are resistant to bad environments and will have very broad prospects for application.

4. Single Longitudinal Mode Solid State Lasers

Seven years ago, the spectral line width of single longitudinal mode or frequency YAG laser devices was 100kHz. Moreover, they were none too stable. After a few minutes, it was necessary to adjust them. Currently, Stanford University has already taken line or ray

width and compressed it again. Early this year, the compression was to 30Hz. In May, the compression was to 3.8Hz. It is predicted that, in September, the compression will be to 0.1Hz. They acknowledge that, due to the fact that the gain of YAG is very high, the acuity or sharpness of the resonance chambers is capable of exceeding 20,000. Very quickly, they will then be capable of taking frequency instability and compressing it out. This type of narrow line or ray width, single longitudinal mode or frequncy solid state laser is very useful in optical radars as well as other high sensitivity detection and probing systems.

5. Adulterated Nd Yttrium Lithium Fluoride (YLF) Laser Devices

This type of laser device will abruptly increase in the amount of its sales in the coming two or three years. Comparing with Nd:YAG crystals, Nd:YLF acts as a gain medium for super short pulse laser devices. It possesses the advantages below: (1) a 3 times wider flcuresent spectral line or ray, helpful in producing super short pulses; (2) an upper energy level life twice as long, high effective stored energy, high Q switch output: (3) small dependence of the index of refraction on temperature, the reason for this being that, under light pumps, the focus of heat concentration is small, and, when output power is continuously adjusted, light bundle or beam characteristics are, in reality, not altered; (4) low rates of heat conductance link together with the previous advantage, and, when cooling water flow speeds undulate, undulations in output power are small. In YLF laser devices using semiconductor laser pumps, when sound and flash are adjusted Q, the peak to peak instability of output is better than 3%. Due to the reasons above, YLF crystals which have already appeared in the U.S. are in a situation where supply does not meet demand. At the present time, there are only the two companies, Union Carbon and Airtron, producing YLF crystals. However, in the crystals, the scattered particles have still not been eliminated very well. Finished product rates are relatively low. In particular, supplying large dimension crystals is relatively difficult.

6. Lamps Used in Pumps

As far as making semiconductor laser devices using pumps is concerned, due to power and price limitations, within a short period, it is still not possible to completely replace pump lamps. Although the production of pump lamps has more than twenty years of history, due to mass production being inadequately large, manufacture is still dependent on hand work, however. The equipment is relatively simple, and product quality is primarily dependent on the skill of worker operations and strict management of industrial techniques in order to guarantee it. In the last few years, due to the special requirements of industrial use laser equipment and the areas of aeronautics and astronautics, the life of lamps has already clearly increased. Pulse xenon lamps are generally 10^6-10^7 iterations. Lamps used for aeronautics and astronautics are capable of reaching 10^3 (pump chrysoberyl) to 10^9 (pump YAG) iterations. Continuous krypton lamps, by contrast, from a general 200-400h, increase to 600-10000h.

(II)

In the area of laser applications, we came in contact with a relatively great number of profiling or diagraming instruments with microprocessing and industrial processing, as well as medical treatment research which used laser equipment.

1. Laser Microprocessing 3

Laser microprocessing has already become a key processing means in the semiconductor and microelectronics industries. Following along with the development of integrated circuits, the applications of laser microprocessing have become greater and greater. The proof is that the renewal and generational replacement of microprocessing devices and the generational replacement of integrated circuits have occurred in step with each other. For example, 9 years ago, when the 64K DRAM (Dynamic Random Access Memory) went into production, the esi Company put out the 80 Model laser processing device. In 1983, when the 256K

DRAM went into production, and the numbers of the 64K DRAM produced increased to more than 250 million units, the 8000a Model was introduced to the world. In 1986, when the 1M DRAM went into production, the 8000c Model device came out. At the end of the following year, they also added the Hyper-Laplace technology associated with the making of extraneous or superfluity corrections during the process of operations. In 1988, the 9000 Model came out. It brought with it its own superclean chamber and ranipulators. Positional or stationing accuracy went up to 0.5μm, in order to mate up with the 4M DRAM which was then going into production. This type of synchronisity phenomena are amply explained by the latent powers and advantages of laser microprocessing. Besides laser resistance value microadjustments and extraneous or superfluity corrections, the uses of laser microprocesing have already expanded in their development to other related fields. Among these are included special use integrated circuits (ASIC) associated with laser program design, GaAs and linear integrated circuit processing, and other similar items. ASIC laser programing design is capable of economizing on the control of covering templates and very, very greatly shortening the manufacturing time for ASIC prototypes in this type of work sequence-- which wastes effort and time-- saving funds. Laser template repairing devices are already being sold as commercial products. They use two laser devices. One is a Q switch frequency multiplier Nd:YAG laser. It is used in order to burn off nontransparent flaws (excess) on cover templates. At a minimum, it is possible to repair dimensions $0.5 \pm 0.1 \mu$m. The other device is an acoustoptical modulation continuous Ar ion laser. It makes use of laser CVD methods to repair flaws associated with vacant positions or gaps. At a minimum, it is capable of repairing dimensions of $1.0 \pm 0.1 \mu$m. The complete device comes paired with a large amount of software. Operation is simple and convenient, fast, accurate, and it is capable of clearly increasing the product finishing rates for covering templates, achieving excellent economic benefits. Laser character or letter carving devices (also called carvers or engravers and marking devices) have already gone into mass production. Several plants have annual production quotas of several hundred devices. They are capable of

carving characters or letters, incising diagrams, engraving dial plates, and serial numbers. Due to there being no contact, there is no contamination, and the thermally influenced area is small. In the microelectronics industry, they are very welcome indeed. They also have applications in other industries. In order to develop submicron accuracies and degrees of linear directionality, besides making use of frequency multiplication, quasimolecular laser devices, and other similar technologies, there are already a number of units which are in the midst of aggressively studying the use of strong laser light (for example, high average power solid state laser devices) to excite soft X rays to carry out microprocessing.

2. 100 to 400W Solid State Laser Processing Is Already Familiar

Representative of this are the Raytheon Company's SS484, SS525, and SS550 Models as well as the Control Laser Company's 440-8 Model and 440-16 Model. These industrial laser processing devices are all capable of being used in punching holes, cutting, and welding. The most frequent use is welding. The special features they have in common are that pulse widths, within a very wide range (0.13 to 10ms) are variable, in order to be appropriate to different processing requirements. Outputted laser light is capable of going through soft optical fiber distribution and transmission to processing devices. The fiber transmission losses are approximately 2-3%. The work platforms are moveable in three dimensions. Some, in order to guarantee the stability of the working platforms, opt for the use of granite rock to act as a base. When cutting metal, the cutting speed can be increased by blowing oxygen gas. The blowing of Argon gas is capable of making the cut apertures clean. They can operate 24 hours a day, six days a week. Changing lamps is convenient and can be completed within 5 minutes. It is not necessary to readjust the light path. According to what the Raytheon Company says, these types of products from this company alone are, at the present time, in use at production sites in numbers of approximately 700-800. It is possible to see the size of the market.

3. Laser Contour Devices

This type of device is mounted on aircraft or helicopters in order to carry out high repetition frequency measurements of the

surface of the ground, the surface of the sea, or the surface of ice. This supplies measured sketch diagrams of the contours on the surface of the earth. They are also capable of being mounted on moving surface detection targets. They are capable of using GaAs laser devices. The frequency of repetition is 4kHz. Wave bundles or beams are lmrad. It is possible to select the first returning wave pulse or the last returning pulse. The operating distance from the ground surface is 600m. From waves, it is 500m. From ice, 1500m. At a minimum, it is possible to measure distances of 5m. If the aircraft is flying at a speed of 400km/hr, then, the measurement density reaches one point each 2.5cm. Making use of Nd:YAG laser devices with lamp pumps, the repetition frequency is 30 Hz. When aircraft are flying at a speed of 400km/hr, the interval between measured points is 3.7m. The effective distance is 10km (with targets working together, 30km). Single iteration measurement accuracy is $\pm$10cm. 64 iteration averages reach $\pm$1cm. They are also capable of using Nd:YAG laser devices. Repetition frequencies reach as high as 10kHz. The key technology in this set of systems is the constant ratio timing device. According to what the Holometrix Company says, they are just in the midst of setting up ways to take single iteration measurement accuracies and raise them to 5mm. In order to guarantee the safety of people's eyes, specially designed eye safety limiting devices are capable, on the basis of user requirements, of limiting the azimuth, angle of elevation, and minimum distance of the laser light emmiting instruments. The Company raised a number of actual examples of applications of these devices. For example, on Luopu (phonetic, possibly Lawford) Island in the State of Virginia, they sketched out measurements of buildings 36ft (11m) high, trees, and the semicircular form of a moveable building's tower structure, prefabricated using corrugated iron. It was also possible to see an aircraft hangar. It was possible to discern the front and back walls as well as the slants on the roofs of buildings. On the basis of what was said, compared to conventional methods of measurement, using contour devices to measure was capable of saving 99% of costs. This type of instrument, for the most part, is produced for the three

services--Army, Navy, and Air Force. They are also provided for use in such areas as agriculture, oil fields, and so on.

4. Laser Equipment for Uses in Medical Treatment and Scientific Research

Due to the limitations of the relevent laws and regulations, there are a number of pieces of laser equipment for medical uses which have clinical applications but have not yet been approved, except for use in scientific research on medical treatment. We saw two types of this sort of equipment. One type is the Quantronix 1500 Model laser device. It is fitted together into a set with a type of duct associated with the technology of forming or shaping air sacs and blood vessels. It is used in research on the technology of forming and shaping blood vessels. In order to be appropriate to the requirements of research, the output power of this type of laser device is capable of being adjusted from 1W to 45W (multiple mode or frequency); each step is 1W. The pulse duration is capable of being adjusted from 1s to 30s; each step is 1s. Laser devices make use of SMA model connectors and ϕ 125μm fused quartz fiber connections. Over ten pieces of this type of equipment have already been produced. The other type is Er:YAG laser devices. Their output is 2.94μm laser light. At the present time, it is also only providing uses in scientific research on medical treatments.

(III)

From this visit of ours, we also have a number of superficial understandings of U.S. scientific research on lasers and of production management. Our relatively deep impressions were the three points below:

1. A high level of attention paid to preliminary research, commiting very strong manpower and financial resources. An example would be the Livermore Laboratories. They have approximately 1 thousand people making laser devices. Among these, one in eight are PhD's. There are forty or fifty people managing research on advanced laser technology. On average, each person's annual scientific research expenditures are $150,000 U.S. In the area of nonlinear crystal research, they have opted for the method of "throwing out a

big net". On the foundation of theoretical analysis calculations, they make use of powder form multiple crystals and small dimension crystals (for example, a few millimeters) for making analytical tests. After they have the symptoms of trends, they, again, make tests with large dimension crystals. In this way, it is possible to simultaneously study up to a hundred types of crystals, shortening the period for test manufacture, and economizing on test manufacturing expenses. University professors compete with each other in requesting basic research projects. After preliminary research work achieves definite results, then it is transfered over to production plants to carry out the initiation of production type studies (for example, "plank" or "strip" type solid state laser devices). Of itself, it then jumps out of one's hands, making room for the handling of new, even more advanced research projects. From start to finish, it goes through at the forefront of scientific and technological development. They acknowledge that the competition in basic research work is invisible, but, for all of that, it is intense. Persons who undertake projects must specify a period (normally, it is a quarter) and write a work report. Work which makes a lot of progress is then capable of receiving funding according to plan. The next time a request for a new project is made it is also easy to approve it. Although they do not opt for the use of comparative evaluation methods with the results of scientific research project by project, each scientific researcher, however, takes very tender care of his or her own reputation, strives diligently to create something new, and competes with all of his or her strength to be outstanding. If this is not the case, then, later on, it is difficult to obtain financial aid.

2. Striving in all ways possible to shorten the testing and manufacture period for new products, adapting to the requirements of intense market competition. The principal means for companies to shorten the test and manufacture periods for new products is to opt for the use of computer assisted design (CAD) and computer assisted manufacture (CAM). Almost all the companies we looked at--large and small-- had CAD. This even extended to each design engineer's workstation having CAD terminals, to use when they pleased. These types of equipment are very expensive. However, in order to survive,

they do not stint on the large amounts of money for the purchases. Many companies have very low profits. However, they still do this sort of thing. After opting for the use of CAD and CAM, in the past, it has required approximately 5 years to put out a new product. Currently, this has been shortened to 2 to 3 years.

3. Quality consciousness has permeated into every link of production and management. For example, the various companies, on the basis of the requirements of product quality, set up a production environment of appropriate cleanliness. Moreover, the research workshops initiating new products are still better than the production shops. Another example is that strict checks, tests, and records are carried out for all raw materials and semi-finished goods. Some companies, on production lines, set up scanning electron microscopes, preparing randomly to do checks and tests of suspicious materials discovered during production. Some companies carry out detailed inspections, measurements, and records on each of the various parameters of each laser rod used in laser devices (dimensions, processing accuracy, plating membrane quality, laser light threshold values, laser efficiency, and other similar items). There was one company which made lamps. Each lamp was required to go up on a laser device which acted as a standard for checks and measurements to check out its luminous efficiency. We were deeply impressed by the personnel of these companies. From top to bottom, they were sincerely conscious that quality was life itself. Everyone put quality in first place.

Participating in this visit outside China were Zhang Weizhong, Mei Suisheng, and Huang Qiaohua. The duration of this visit was relatively short. We were "looking at the flowers from a moving horse." Our understanding of the situation was not deep or complete. However, we feel that what we did obtain was not inconsequential. We venture to write these impressions to give to those within China the chance to participate with us on the visit.

MEETING REPORT

THE FIRST "SEMINAR ON THE DEVELOPMENT OF DISPLAY TECHNOLOGY FOR MILITARY USES" TAKES PLACE IN NANJING

The National Defense Science and Industry Commission's relevent special projects teams combined to call the first "Seminar on the Development of Display Technology for Military Uses" from 19-21 September in Nanjing. Particpating at the meeting were professors from over 30 units such as the National Defense Science and Industry Commission, the various branches of the armed forces, leading organizations and research institutes of the Electromechanical Department, high level institutes and schools, plants, and other similar institutions. A total of over 50 experts were represented. They came, respectively, from user departments, departments associated with the test manufacture of complete devices, and departments associated with the test manufacture of instruments. The meeting, on the basis of a spirit of needing to pull forward and propel the development of technology, carried out earnest discussions on the key questions which need to be resolved, such as, the current state, the future prospects, and the main directions of attack for the military applications of display technology.

Display technology is using visual methods to supply information to people. The amount of the information, the density of the information, the speed, and the completeness are far better than for hearing, smell, touch, or taste. Because of this, it is the most effective means of taking information and transmiting it to people. The importance of display technology in modern warfare has already come to be known to people with every passing day. The development inside China and outside has been very rapid. Setting out from the angle of applications, it can be roughly divided into the three types of cathode ray tubes (CRT), head level displays, and large screen displays.

The one which appeared earliest was the CRT. It is already widely applied in various types of display systems. Within China, currently, there are a considerable number of plants, offices, institutes, and schools which are capable of test manufacture and

production. Equipment functions, production quality, reliability, as well as the degree of standardization are in the process of being gradually increased. Some products have already operated stably in units for many years, obtaining good comments from the using units. However, from the aspects of completeness, systematic nature, standardization, as well as the conversion to the domestic production of the instruments, a number of problems still exist. A number of high quality CRT's still depend on imports.

Large amounts of head level display technology are applied in command, control, communications, and intelligence systems, various types of small and medium model computers and intelligent computer terminals, communications systems, electronic warfare systems, shipboard displays, aircraft and vehicle displays, and various other similar areas. Instruments have plasma body displays (PDP), liquid crystal displays (LCD), fields causing the emmission of light (EL), vaccuum flourescent displays (VFD), and so on. Outside of China, PDP have already been made into a 2048x2048 line monochrome large model plate. EL, VED, and LCD all have 640x400 line or even larger products. PDP, EL, VFD, and so on, have multiple colors and full color prototypes under study. 14in color LCD-TV was capable of going into production in 1990. Within 3-5 years, 18in-30in are capable of being introduced. In conjunction with this, research has even begun on a 40in. Our country, in head level displays, special types of displays for military uses, as well as test and measurement instruments, and other similar areas, already has PDP, EL, LCD, VFD, LED, ECD, microchannel plates, as well as other special types of displays, and so on, brought to fruition and in production. However, compared with outside China, it goes without saying, the test production levels or equipment for industrial techniques are still all a definite way off the mark.

In relatively high level military command departments, there is often a requirement for large screen displays. Although their amounts of information are not necessarily greater than those of ordinary display devices, due to the size of the screens, however, the good quality results from direct view, and, moreover, their being capable of joint use by numerous people, they are convenient to studies

producing policy decisions. Among the ways for them to be actualized, there are CRT projection systems, liquid crystal and solid projection light valves, luminous diode arrays, plasma plates, and so on. For example, a Belgian company uses three tubes projecting onto a screen reaching 7.2m in diagonal line. Its polyfocusing system guarantees that the three color imagery projections on the screen completely overlap. The British Dwight Cavendish Company has test manufactured an SD270 laser optical frequency projector device. Nonlinear display projection dimensions reach 15m. From the three red, green, and blue bundles of laser beams, respectively going through crystal modulation, they form one bundle or beam. The contrast is capable of reaching 1000:1. The geometrical precision reaches 99.9%.

Among the meeting representatives, it was recognized that, with regard to the problem of CRT development, at the present time, in display technology, it still occupies an important position. Moreover, it is predicted that it will still maintain it for a period of time. With regard to head level display technology, the experts suggested that it should be given the serious attention which it needs and the support which it should have. With regard to such technologies as large area photoetching, large area precipitation or depositing of thin films without gaps, and multiple resolution electrode lead-outs, equipment systems, key materials and drive circuits need to be given the serious attention which they require. Attacks need to be organized on the key points, and solutions pieced together. With regard to the problem of the development of large screen displays, it is necessary to satisfy an information capability for removal or update. The turn on preparation time must be within 3-5 minutes. They must be multicolor, and the best is panchromatic. Imagery and figure displays need to be compatible. They must be able to "mate up" with user CRT display devices in various aspects.

The representatives attending the conference resolved, for the sake of the development of display technology for military uses in our country, to unite, cooperate, and struggle together.

(Zhou Wenyang reporting)

HIGH POWER SOLID STATE LASER DEVICE RESONATION CHAMBER DESIGN AND BEAM PARAMETERS ASSOCIATED WITH WIDE RANGE THERMAL STABILITY METHODS

Li Shichen Ni Wenjun Yu Jian Hu Guojiang Li Yingxin

This article discusses the design principles of high power solid state laser device resonation chambers. It points out the limited nature of the normal thick lens equivalence methods. As a result of this, it gives the theory of designing resonation chambers using light beam parameter self-consistent or self-agreeing methods. It analyzes thermodynamic characteristics of media chamber light beam parameters for type lenses and puts forward a new type of high power wide range thermal stability chamber.

I. INTRODUCTION

At the present time, garnet is what is attracting people's attention in the development of high power laser devices. Single rod Nd:YAG laser device outputs have already exceeded 400W. Multiple rod series connection chambers already exceed 2kW. Each rod pump power reaches as high as 16kW. The corresponding media thermal focusing distances are as small as to be appropriate to the length of the rod or even smaller. This will give light chamber design as well as output light beam characteristics new problems to put forward. The traditional method is to take type lens or lens like media approximations of thick optical lenses and move forward with them as being equivalent to thin lens chambers verified by the use of g parameters. As a result of this, g parameters were used to describe chamber characteristics, and, in conjunction with that, to design resonance chambers. However, in situations with high power pumps, this type of equivalency is limited. As a result of this, it is possible to create errors. Because of this, we brought forward methods based on Gauss light beam parameter matching concepts in order to design resonance chambers. The latter are related to the problems of thermal stability chambers. Traditional concepts of passive or active optical resonance chambers or resonators have chamber lengths which are fixed and unchanging (in order to facilitate comparison, the ones this article talks about were rigid chambers). It was not difficult to demonstrate rigid chambers which include heat induced lens like media are ones which do not show the existence of any

thermal stability at all. The definition of thermal stability is refering to output light beam parameter heat invariability. As a result of this, what are normally called heat stability chambers, within the catagory of rigid chambers, in actuality, are non-existant. Because of this, this article attempts to break through the restraints of this type of traditional rigid chamber thinking. It puts forward a type of single or unitary auxilliary adjustment control or tuning chamber length parameter in order to adapt to when pump powers change in wide ranges, and beam paramters still maintain stable, invariable chamber structures (called pliable or flexible chambers). As far as laser devices which possess this type of chamber structure are concerned, in principle, it is possible, within the full range of power, to operate normally. Obviously, this has great practical significance.

As far as the two questions of chamber design and thermal stability chambers which this article discusses are concerned, not only are they appropriate for use with solid state media chambers. In principle, they are also appropriate for use with any lens like media resonance chamber.

II. SOLID STATE LASER MEDIA IN STATES OF STRONG EXCITATION

At the present time, high power solid state laser devices still use lamp pumps and rod shaped media for the most part. Various types of heating systems add heat to rods and cool the surfaces of rods. Within the rods, they form radially directed heat conduction currents. As a result of this, they produce a radially directed temperture field $T(\rho)$. Giving consideration to rod forms of limited length and thermal field boundary conditions in the vicinity of the end surfaces of rods, as well as angular temperature field induced pump non-uniformity, they should be a three dimensional thermal conductance problem. However, in the actual situations, the latter two influences, as compared to the former, are generally capable of being ignored. Because of this, it is permissible to only consider the radially directed temperature field $T(\rho)$ as well as the radially directed gradient and the thermal stress-strain field associated with $T(\rho)$ formation rates of refraction. The latter also goes through changes in rates of refraction given rise to by photoelasticity effects.

As a result of this, the functions for the overall rate or index of refraction given rise to by thermal effects are written as [1]

$$
\left.\begin{aligned}
n &= n_0 + \Delta n(\rho)_T + \Delta n(\rho)_s \\
&= n'_0 (1 - 2\rho^2/b^2) \\
n'_0 &= n_0 + \gamma P_{in}/l \\
b^2 &= (\beta l \rho_m^2 / P_{in})(1 + \gamma P_{in}/l n_0)
\end{aligned}\right\} \qquad (1)
$$

In the equations, n_o is the medium index of refraction; n'_o is the axial value of indices of refraction considered and related to temperature. It is a weak function of P_{in}; P_{in} is the pump electric power (kW). l is the rod length. ρ_m is the radius of the rods. γ and β are constants related to qualities of the media. 7 For example, with regard to the Nd:YAG crystal running along the rod axis in direction [111], the index or rate of refraction coefficients in the x'y' main ellipsoid axial directions are

$$\beta_{x'} = 11.1 \times 10^{3} \mathrm{kW/cm}$$

$$\beta_{y'} = 14.4 \times 10^{3} \mathrm{kW/cm}$$

$$\gamma_{x'} = 1.45 \times 10^{-5} \mathrm{cm/kW}$$

$$\gamma_{y'} = -6.66 \times 10^{-6} \mathrm{cm/kW}$$

It is possible to see that, with regard to Nd:YAG, n_o=1.825. As a result of this, the γ quantity is a negligibly small amount.

(1) Form or pattern type media are generically designated as lens like media. The propagation behaviour of light rays within them is capable of being described with the use of the well known light ray equation [2]

$$\frac{d}{ds}\left(n \frac{d\rho}{ds} \right) = \nabla n \qquad (2)$$

s is the measurement of the distance of a given fixed point along the light ray. ρ is the position vector of the point s. With regard to near axial light rays, it is possible to make use of d/dz as an approximate substitute for d/ds. As a result of this, (1) substitutes into (2), and one obtains

$$d^2\rho/dz^2+4\rho/b^2=0 \tag{3}$$

The general solution is

$$\left.\begin{aligned}\rho &= \cos(2z/b)\rho_0 \\ &\quad + \frac{b}{2}\sin(2z/b)\rho'_0 \\ \rho' &= -\frac{2}{b}\sin(2z/b)\rho_0 \\ &\quad + \cos(2z/b)\rho'_0\end{aligned}\right\} \tag{4}$$

In these, p_o and p'_o are incoming light ray parameters at the location z=0 (light beam radius and rate of slope). Because of this, the ray matrix for media with length l is

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} \cos(2l/b) & \frac{b}{2}\sin(2l/b) \\ -\frac{2}{b}\sin(2l/b) & \cos(2l/b) \end{pmatrix} \tag{5}$$

Taking a medium for which the index of refraction penetrating into the medium is n_1 (Fig.1a), and, in conjunction with this, using n_o as an approximate substitute for n(r) at the incoming and outgoing radiation points establishing the boundary surface, and, then, taking l to be the reference plane system matrix, it is possible to write

$$\begin{pmatrix} A_1 & B_1 \\ C_1 & D_1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & \frac{n_0}{n_1} \end{pmatrix} \begin{pmatrix} a & b \\ c & d \end{pmatrix} \tag{6}$$

$$\cdot \begin{pmatrix} 1 & 0 \\ 0 & \frac{n_1}{n_0} \end{pmatrix} = \begin{pmatrix} a & b/n_0 \\ n_0 c & d \end{pmatrix} \Bigg|_{n_1=1} \tag{6}$$

$n_1 = 1$ represents air.

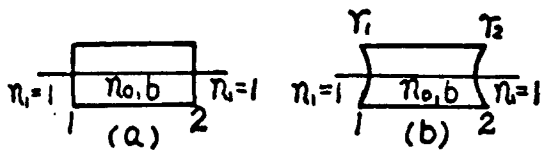

Fig.1 (a) Ordinary Flat End Surface Rod (b) Rod With Ground End Surfaces

As a result of this, the focal length of the system in question f and the main surface position h are

$$f = -1/C_1 = b/[2n_0 \sin(2l/b)] \tag{7}$$

or

$$h = (D_1 - 1)/C_1 (\text{或} = (A_1 - 1)/C_1) = (b/2n_0)\tan(l/b) \tag{8}$$

With regard to the vicinity of the two end surfaces of rods with limited lengths, in order to compensate for thermal effect changes in the rods as a whole, making their lengths non-uniform, and leading to additional positive lens effects, even if one is at very high pump powers, relative to equation (7), they are still an altogether negligiblly small quantity[1]. As a result of that, this article does not consider them.

Besides this, in order to compensate in thermal focal length, there are already people [3] who attempt to take the end surfaces of rods and grind a concave surface on each one with a respective radius of curvature of r_1 and r_2, as is shown in Fig. 1b. At this time, the medium matrix is capable of being written as

$$\begin{pmatrix} A_2 & B_2 \\ C_2 & D_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{n_1 - n_0}{n_1 r_2} & \frac{n_0}{n_1} \end{pmatrix} \cdot \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{n_0 - n_1}{n_0 r_1} & \frac{n_1}{n_0} \end{pmatrix}$$

When $n_1=1$, it is possible to calculate

$$\left.\begin{aligned} A_2 &= a - (n_0 - 1)b/(n_0 r_1) \\ B_2 &= b/n_0 \\ C_2 &= n_0 c - (n_0 - 1)^2 b/(n_0 r_1 r_2) \\ &\quad + (1/r_2 - 1/r_1)(n_0 - 1)a \\ D_2 &= (n_0 - 1)b/(n_0 r_2) + d \end{aligned}\right\} \qquad (9)$$

In these, a, b, c, and d are the elements of matrix (5). Here, we 8
specify Fig.2's $r_1 < 0$, $r_2 > 0$, and we make $r_1 = r_2 = r$. At that time, from (9) and (5), one calculates out

$$1/f = -C_2 = [2n_0/b - (n_0 - 1)^2 b/(2n_0 r^2)]\sin(2l/b) - [2(n_0 - 1)/r]\cos(2l/b) \qquad (10)$$

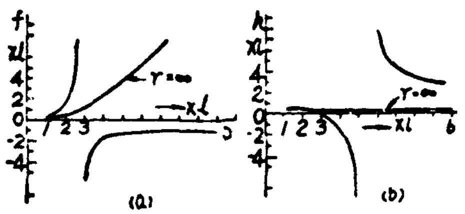

Fig.2 a) f(b) Curve b) h(b) Curve

图2 a) f(b)曲线 b) h(b)曲线

$$h = [(1 - n_0) b/(2n_0 r) + \tan(l/b)] / \{2n_0/b - (n_0 - 1)^2 b/(2n_0 r^2) - [2(n_0 - 1)/r] \cot(2l/b)\} \tag{11}$$

It is possible to see that this type of ground compensated rod, with regard to the variable b, has existing in it points of discontinuity. This is easy to understand.

As far as the current high power Nd:YAG laser device is concerned, each rod's dual lamp pumps have electric powers which reach as high as 16kW (that is, P_{in}). Making use of equation (1)'s expression b and equation (7), it is possible to calculate out the thermal focal length for this time as being roughly appropriate to rod length, even to the point of being somewhat small. This will bring with it certain difficulties for single rod cavity designs (see the explanation that follows). In order to improve this type of short focal length situation, one compensation method is precisely to grind the end surfaces of rods, causing them to obey (10) and (11) above. For example, when one wants to take f = 1 and compensate until f = 5 1, it is possible, on the basis of the steps below, to do it. first, make f = 1. From equation (6), one obtains the transcendental equation

$$\sin(2l/b) = b/(2n_0 l) \tag{12}$$

Taking Nd:YAG as an example, select n_o = 1.83, and solve (12) to obtain

$$b \simeq 2.57\, l \tag{13}$$

Take (13) and f = 5 1 and substitute into (10). It is possible to obtain

$$r = 1.725\, l \tag{14}$$

After this grinding, the f(b) and h(b) characteristics of the rods in question are capable of being obtained from (13) and (14) respectively substituting into equations (10) and (11). The numerical value calculation results are shown in Fig.2. In order to facilitate comparison, simultaneously draw out curves for $r = \infty$. From the graphs, one sees that, as compared to the uncompensated situation with $r = \infty$, the f and h of the ground rods are both very limited in the number of allowable values selected for b. Moreover, within this allowable number, df/db and dh/db both become large. Both these are drawbacks which come along with this type of rigid compensation measure. Because of this, the degree of compensation must be selected appropriately.

III. HIGH SOLID STATE LASER HARMONIC CAVITIES

Speaking with reference to the design problems associated with optical cavities, it seems that they are still summed up as being equivalent to the problems of handling single lens or multiple lens cavities, that is, using equivalent g parameter methods to design Gauss chambers, metastable cavities or chambers, or non-stable cavities. However, there are three special points about high power situations: (1) the thermal reaction parameter b is very small (the thermal focal length is very short). This often causes the light cavity structural parameter calculation values to be impermissible for actual structures; (2) high power loss problems associated with laser media and cavity lenses, as well as other similar elements within the cavities must be dealt with earnestly; (3) due to the fact that it is not possible to again satisfy the condition $b \gg 1$, the normal thick lens equivalency treatment is subject to limitations. The reason for this is that it is not capable of descibing the light ray behavior within the interiors of media. As a result of this, normal g parameter design methods are again inapproriate for use.

1. Single Medium (Rod) Cavity Design

We, first of all, enter the discussion from a habitually utilized planar single plane metastable cavity or chamber. Assume that one takes lens like media to act as the equivalent of equations (6) and

(7). Then, the single lens cavity g parameter equations are capable of being written as

$$g_1 g_2 = (1 - L_2/f)(1 - L_1/f)$$
$$= 0,\ 或\ 1$$

These respectively apply to the cofocal structure cavity as shown by the solid lines in Fig.3a $L_1 = f$, L_2 = anything, and the conjugate point light ray cavity or chamber as shown by the solid

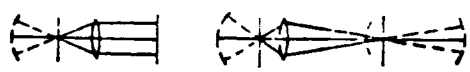

Fig.3 Various Types of Metastable Cavities Possessing Conjugate Point Light Rays

lines in Fig.3b $L_1 < f$, $L_2 = fL_1/(f-L_1)$. For example, when f = 10cm, $L_1 \leq f$ is a set up which is, in actuality, not permissible. Even if it is possible to make a rèsolution with methods involving end surface concave alterations or making use of various types of spherical surface lens media cavities as in the Fig. (broken lines) to resolve the situation, there still exist the problems set out below, that is, in metastable or non-stable cavities, rod light striations having, in principle, to fill up the rod end surfaces (during periods of high power, to avoid additional light diaphragms). Due to shortcomings in the end section cooling conditions and the end surface edge positions often being optically imperfect (processing and AR membranes), the result of this is that, at these places, it is possible to form light loss "foci of infection". Besides that, one should also avoid the planar wave structure of Fig.3a. In particular, this applies to using high repetition frequency pump type operations. In conjunction with this, at times when extremely limited thermal

diffusion rates (Nd:YAG is approximately $0.046cm^2/s$) and heated pulse speeds severely lose equilibrium (the interval between pulses < thermal relaxation time), then, the actual thermal reactions are capable of being even larger, as compared with average pump power. This is even to the extent that, basically, it is possible, on the basis of amplitude values for pump powers, to do calculations, leading to the thermal focal length being even shorter. At this time, one end of a rod presents planar incoming wave radiation. The other end surface's light striation or spot radius $\rho = \rho_0 \cos(2\ 1/b)$ is capable of being very small. As a result of this, the optical load is extremely large. As far as overall causes are concerned, again adding to the high thermal sensitivity characteristics of metastable cavities or chambers themselves is generally not appropriate for use with high power laser devices. As a result of this, this article advocates the use of Gauss cavities or chambers. As a result of this, it puts forward methods for the design of resonance cavities or chambers using Gauss light beam self-consistency principles. The basic concept is that, with a given value of $b(P_{in})$, one calculates out the required light beam parameters for inside and outside the rod. Following that, one selects cavity structure parameters R_i and d_i (Fig.4) and makes them consistent with these given beam parameters. As a result of this, one forms the light cavity or chamber. For example, let the largest light striation or spot in the medium be located at the place 1 / 2 at the center of the rod (it is advantageous for modular volume, modular suppression energies, restraining end surface light striations or dots, and other similar items), and it is then possible to complete the design. What is being said is explained below.

Because of the fact that, in actual solid state laser devices, the medium interior is not capable of realizing the extremely large beam striation or spot associated with one of more, it follows as a result that $\rho_{max} = \rho_{1/2}$ is capable of being obtained from the condition

$$d\rho/dz|_{z=l/2} = 0 \tag{15}$$

Because of this, from equation (4), it is possible to obtain

$$\rho_0' = (2\rho_0/b)\tan(l/b)$$
$$\rho_{l/2} = \rho_0[\cos(l/b)$$
$$+\sin(l/b)\tan \qquad (16)$$

$$(l/b)] \qquad (17)$$

The origin point of the z coordinate in the various equations above is the left end surface of the rod (Fig.4). With regard to light rays outside the rod, one takes the z coordinate origin point and translates it to t_{01}. Then, it is possible to borrow the use of the ready made Gaussian beam propagation formula

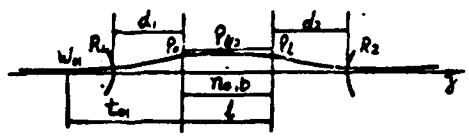

Fig.4 Single Medium Resonance Cavity with Light Beam Parameter Symmetry

$$w^2(z) = w_{01}^2[1 + (\lambda z/\pi w_{01}^2)^2]$$
$$dw(z)/dz|_{z=t_{01}} = [w_{01}^2/w(t_{01})] \qquad (18)$$

$$(\lambda/\pi w_{01}^2)^2 t_{01} \qquad (19)$$

Let

$$w(t_{01}) = \rho_0 \qquad (20)$$

Then, on the basis of the Snell Law, one has

$$dw(z)/dz|_{t_{01}} = n_1\rho'_0 \tag{21}$$

Because of this, from (16), (19), (21), and (18), one has

$$[\tan(l/b)] \tag{22}$$

$$\rho_0^2 = w_{01}^2[1+(\lambda t_{01}/\pi w_{01}^2)^2] \tag{23}$$

Obviously, if ρ_0 and ρ'_0 are already determined, then, the Gaussian beams inside and outside the medium have been uniquely and precisely determined. We make use of the beam waist w_{01} and the waist location t_{01} in order to represent this Gaussian beam. It is capable of being obtained from connecting together equations (22) and (23). The result is

$$\begin{aligned} w_{01}^2 &= \rho_0^2/\{1+[2\pi n_0\rho_0^2+\tan(l/b)/b\lambda]^2\} \\ t_{01} &= 2\pi^2 n_0\rho_0^2\tan(l/b)w_{01}^2/b\lambda^2 \end{aligned} \tag{24}$$

In high power situations, the first term of the fraction in equation (24) is much larger than 1. As a result of this, an adequately precise result is set out below.

$$w_{01} = \lambda b/2\pi n_0\rho_0\tan(l/b) \tag{25}$$

$$t_{01} = b/2n_0\tan(l/b) \tag{26}$$

On the basis of Gaussian beam characteristics, the radius of curvature of wave surfaces is

$$R_l = (t_{0l}-d_l)\{1+[\pi w_{0l}^2/\lambda(t_{0l}-d_l)]^2\} \tag{27}$$

Symbol specifications are set as: $d_{i(illegible)}$ is always positive, and t_{0i} and R_i symbols and the normal Gaussian light beam mathematical definitions are in line with each other.

Up to now, single lens cavity design has already been resolved with the procedure set out below: (1) given $b(P_{in})$, 1 and ρ_m; (2) consider the relationship to the radius of the rod, selecting ρ_0 (or $\rho_{1/2}$); (3) from equations (25) and (26), solve for parameters w_{01} ($=w_{02}$) and t_{01} ($=t_{02}$); (4) from the permissible conditions of the geometrical structure or the actually required selections for d_1 and d_2, it is also necessary to give consideration to whether or not the numerical values of R_1 and R_2 are reasonable; (5) from equation (27), calculate out R_1 and R_2. However, in the equation, the selected values of d_i must not only be permissible with respect to the geometrical structure, they must also make R_i suitable.

At this point, let us put forward a concept. At the center section of the rod, let one grind a slight "shinbone" section in order to facilitate even more effectively giving rise to aperture radius limitation mode diaphragm effects. This may also be advantageous for raising the quality of the output beam. This even extends to being able to achieve high power TEM_{00} mode.

Pointing out some additional things along the same lines with regard to medium and low power solid state lasers, due to the fact that b is extremely large, a result of this is that ρ'_0 or ρ'_1 are very small. The results make $w_{0i(illegible)}$ and $t(illegible)_{0i}$ very large (that is, approaching a planar surface wave). At this time, it is possible to discard the requriement to select $\rho_0 = \rho_1$. Moreover, on the basis of requirements and possibilities, one sets up a set of incoming radiation parameters (ρ_0, ρ'_0). On the basis of what was described before, one carries out calculations with light ray tracking methods, again using light beam wave surface matching principles to precisely specify cavity structural parameters. Alternatively, one opts for the use of method [4].

2. Thermodynamic State Characteristics Associated with the Light Beam Parameters of Single Medium Cavities or Chambers

When R_1 and R_2 do not change, the change in b is

$$b^* = b + \Delta b \tag{28}$$

At this time, the situation with the changes in Gauss light beams (that is, w_{0i} and t_{0i}) is:

(1) From equations (25) and (26), when b increases or decreases, w_{01} and t_{01} follow it and increase or decrease. At this time, from equation (27), it is possible to see that, if d_1 and d_2 also change, then, R_i must necessarily be altered. If that is not the case, the original design's condition for symmetry associated with light beam parameters inside rods will not be set up again. ρ'_0 will also not again be capable of using equation (16) in order to express itself. (25) and (26) will become invalid. This type of situation, on the basis of equations (4) and (18)-(21), needs to alter anew the structural parameters of cavities. If this is not the case, there is a possibility of its leading to violent changes in beam parameters and abnormal operation.

(2) Situation in which changes in d_1 and d_2 are permitted: At the time when b changes, w_{0i} and t_{0i} correspondingly change. When one makes R_i invariable, it is possible, from equation (27), to solve for $d_i(b^*)$. If one takes $d_i(b)$ and adjusts it to become $d_i(b^*)$, then, at that time, it is possible to maintain the original design's symmetrical light beam structure. However, the beam parameters still are altered.

(3) We discover that, when b changes, one makes the beam parameters for one of the ends invariable (for example, the left end's $R_{1(\text{illegible})}$, d_1, and w_{01} do not change, and, in conjunction with that, one selects it to be the output end). These conditions are just this simple, and it is only necessary to adjust d_2, and that is all. Obviously, this is a matter of great practical significance. The proof of this is as follows: assume that w_{01} and t_{01} do not change. This means that, as a consequence, ρ_0 and ρ'_0 do not change. From (28) and (4), at this time, ρ_1 and ρ'_1 will change to be

$$\left.\begin{aligned} \rho_l^* &= \cos(2l/b^*)\rho_0 + \frac{b^*}{2}\sin(2l/b^*)\rho'_0 \\ \rho_l^{*\prime} &= -\frac{2}{b^*}\sin(2l/b^*)\rho_0 + \cos(2l/b^*)\rho'_0 \end{aligned}\right\} \tag{29}$$

When one writes out equations (18) and (19) for the right end light beam, one has

$$\rho_1^{*2} = w_{02}^{*2}[1 + (\lambda t_{02}^*/\pi w_{02}^{*2})^2] \tag{30}$$

$$\rho^{*\prime} = (\lambda/\pi w_{02}^{*})^2 t_{02}^*/n_0 \rho_1^* \tag{31}$$

Solving equations (30) and (31) together and using the same steps with equations (25) and (26), one obtains

$$w_{02}^* = \lambda/\pi n_0 \rho_1^{*\prime} \tag{32}$$

$$t_{02}^* = \rho_1^*/n_0 \rho_1^{*\prime} \tag{33}$$

ρ^*_1 and $\rho^{*\prime}_1$ in these equations are determined by equation (29). Again, solving d^*_2 by form (27), it is then possible to obtain a subsequent self-consistent equation corresponding to b^*

$$z_2^{*2} - R_2 z_2^* + \pi^2 w_2^{*4}/\lambda^2 = 0$$
$$z_2^* = t_{02}^* - d_2^* \tag{34}$$

The two solutions to equation (34) are both reasonable. Now, we again take d^* (illegible) and write

$$d_2^* = d_2 + \Delta d_2 \tag{35}$$

We designate Δd_2 to be the compensation function corresponding to b. Δ b is measurable (for example, through measuring P_{in}). Because of this, after we go through the supplying of d_2 with an amount of shift or translation Δ d, we guarantee the invariability of the left end Gaussian beam's w_{01} and t_{01}. This is explained by our finding a new type of thermodynamically stable cavity. It is not only what is called a thermally insensitive cavity, it is different from the

pliable cavity [4]. The reason for this is that this, basically, is a two lens cavity. In this, the analysis and image have been made clearer and more obvious than in the equivalent single lens cavity--also more precise. As a result of this, one also has an explanation of the limited nature of the latter. It does an approximate handling job and only when b >> 1. It needs to be pointed out that this article's putting forward this type of control model cavity overcame the shortcoming of the power of solid state laser devices only being capable of operating normally under fixed excitation. This model is almost capable of operating in a full range of powers. In principle, the permissible range of variation for b is capable of being solved for this way. Let the value of b for when the design acts symmetrically be b_{min}. After that, when $b > b_{min}$, relying on externally controled adjustments of d_2, realize normal operation. The adjustment range is capable of using $\rho'_1 = 0$ in order to do calculations. Because of this, from equations (16) and (31), it is easy to obtain the following for this time

$$\begin{aligned} b_{max} &= 2b_{min} \\ (P_{in})_{max} &= 4(P_{in})_{min} \end{aligned} \tag{36}$$

Of course, this type of control model cavity guarantees the invariability of single side beam parameters. At the same time, it sacrifices the symmetrical nature of beam parameters inside media, despite the fact that, to a very large degree, this makes no difference all. Besides this, it is precisely with regard to this type of adjustment requirement that the selection of numerical values of R_2 should be far away from the minimum Gaussion beam radius of curvature $\pi w^2_{02(illegible)}/\lambda$.

3. Multimedia Series Resonance Cavity Design

As has already been described, under conditions of strong excitation, it is not possible to select metastable cavities. For this, $d_{ij} < f_i+f_j$ Gaussian cavities are also not permissible for actual structures. If one uses equivalent thin lens cavity treatments, at this time, it is a lens cavity which includes equivalent loads. As a result of this, we still opt for the use of

Gaussian beam self-consistent designs for multimedia series connected rod cavities. Assume that we take b_{min} to be the design value, we still select a light beam symmetrical strucuture (which by no means loses the general character of the basic method). The symmetry here indicates the pump and thermal effect symmetry of two rods for rod dimensions $\rho_{1m} = \rho_{2m} = \rho_m$ and $l_1 = l_2 = l_{3(illegible)}$. Light beam parameter symmetry within media, that is, extremely large values for beam striations, are equivalent to being located in the center of the rod. First, we will discuss the two media cavity shown sketched in Fig. 5. At this time, as concerns the 11
given value of b (eliminating the subscript min), one necessarily has

$$(\rho_{01},\rho'_{01})=(\rho_{11},\rho'_{11})=(\rho_{02},\rho'_{02})$$
$$=(\rho_{12},\rho'_{12})$$

Moreover, structures require that $t_{0(illegible)} > 1$ (assume that the lamp electrode length $\simeq$ 1). Assume that b = 2.57 l. From equation (26), one obtains $t_{03} = t_{01}$ = 1.72 l. As a result of this, requirements are met. In the given time ρ_0, one solves for the three symmetrical beam parameters discussed above. Proceeding to the next step, design procedures for precisely determining the cavity structural parameters of designs are completely identical with those for single medium cavities. The same type of design procedure is capable of being generalized to any multirod cavity.

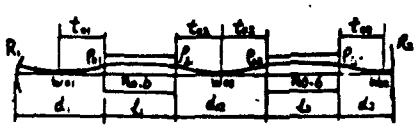

Fig.5 Two Media Resonance Cavity Gaussian Light Beam Self-Consistency

4. Beam Parameter Dynamic Stability Characteristics of Multimedia Series Connected Cavities

Here, in accordance with the two rod cavity in Fig.5, in the same

way as in a situation in which R_1 and R_2 do not vary, there should also exist a simple method to make output beam parameters maintain thermodymanic invariability. The proof is as follows.

When b produces the changes of equation (28), in the same way, make the single side beam parameters ρ_{01} and ρ'_{01} invariable, that is , $\rho^*_{01} = \rho_{01}$ and $\rho^{*\prime}_{01} = \rho'_{01}$. On the basis of the principles of Gaussian light beam propogation, it is possible to make use of the same type of steps as in Section II. From the incoming radiation parameters (ρ_{01}, ρ'_{01}), one calculates straight to the l_2 rod output radiation parameters ρ^*_{12}, $\rho^{*\prime}_{12}$, as well as w^*_{02} and t^*_{02}, obtaining, in form, results of the same type as equations (32)-(35):

$$\left.\begin{aligned} w^*_{02} &= \lambda/\pi n_0 \rho^{*\prime}_{i2} \\ t^*_{02} &= \rho^*_{i2}/n\,\rho^{*\prime}_{i2} \end{aligned}\right\} \tag{37}$$

$$\left.\begin{aligned} z^{*2}_2 - R_2 z^*_2 + \pi^2 w^{*4}_{02}/\lambda^2 &= 0 \\ z^*_2 &= t^*_{02} - d^*_2 \end{aligned}\right\} \tag{38}$$

$$\Delta d_2 = d^*_2 - d_2 \tag{39}$$

In the same way, give d_2 an amount of shift or translation Δd_2, that is, to be capable of compensating for the loss of cavity consistency created by the amount of increase in thermal effects Δb, and, in conjunction with this, maintain the invariability of beam parameters w_{01} and t_{01}. At the same time, one also tolerates a lack of symmetry in the interior beam parameters of rods.

Besides that, in two rod cavities or chambers, there also exists another method to make dual beam parameters invariable. Make ρ_{01} and ρ'_{01} invariable. At that time, obviously, ρ_{i1} and ρ'_{i1} will change to be ρ^*_{i1} and $\rho^{*\prime}_{i1}$. Corresponding with this, w_{03}(illegible) and t_{03} will change to be w^*_{03} and t^*_{03}. Due to this, l_2 and R_2 are shifted or translated as a whole. This only causes $d_{12} = 2t_{03}$ to change to be $2t^*_{03}$, that is to say, to give d_{12} a

$$\Delta d_{12} = 2\,(t^{*}_{03} - t_{03}) = \left(b^{*}/\tan\frac{l}{b^{*}} - b/\tan\frac{l}{b}\right)\Big/ n \qquad (40)$$

that is, the cavity light beams attain a new self-consistency. In conjunction with this, there is a maintaining of the invariable character of (w_{01}, t_{01}) and (w_{02}, t_{02}). At the same time, there is toleration of the loss of symmetry in rod interior beam parameters and changes in the geometry of cavity lengths. As a result of this, we also take these types of adjusted control model stable cavities and, in general, designate them to be pliable or flexible cavities (chambers).

As far as the two types of compensation plans discussed above are concerned, each has advantages and disadvantages. The reason for this is that, for example, if one takes b_{min} to be in a symmetrical light beam cavity designed with initial values, when b changes in an increasing direction, the former is capable of going through a state in which $t_{03(illegible)} \overline{>} d_{12}$ and $\rho'_{02} \overline{<} 0$, and the area or domain of adjustment will also become reduced in size. However, the advantage is that only one lens base is shifted. Moreover, the light beams, from beginning to end, maintain asymmetry or inverse symmetry within two media.

As far as situations in which rod lengths are long and pumps are super strong are concerned, one may as well assist by taking measures for the addition of slight concave adjustments on end surfaces in order to guarantee for certain that the ρ_0 and ρ_{max} ratio is appropriate inside rods. We have already seen reports on the grinding adjustment of the rod ends of 1.4kW YAG laser devices[5].

As far as series connected multiple rod cavities of two or more rods are concerned, when b changes, in the same way, on the basis of Gaussian light beam propagation principles one does recurrence solutions for compensation function Δd_2 or Δd_{ij}. Relying on this adjustment, d_2 or d_{ij} are still capable of reaching the objectives for output light beam parameter thermodynamic stability. The advantages and disadvantages of the two types of regulation or adjustment plans are the same as those described above. When the number of rods is not greater than 4 it is estimated that, only

relying on the adjustment of one single d_{ij} parameter, it is still possible to guarantee quite large domains of thermal stability. If it is to resolve the problem of a small amount of variation in stability, obviously, one opts for the use of the plan for the adjustment of d_2 as being appropriate. The reason is that the dynamic load is small, and it is easy to adjust and control.

IV. HIGH POWER OSCILLATION-AMPLIFICATION SYSTEMS

This is one current plan for high power laser devices. It has often been used with repetition rate modes of operation. Here we are only discussing questions related to the main topic of this article. Assuming an oscillation stage and the opting for pliable or flexible cavities as described above, then, light beam structures within amplification stages are capable of going through oscillation stage output lens form designs and the geometrical distance d_0 between the two stages in order to make precise determinations. There is no repeated influence received from the magnitude of oscillation stage output power. The only influence received is from the pump level itself (b value). If one desires to guarantee that the output beam parameters of amplification stages do not vary, one must only guarantee that the b values of amplification stages do not vary, and that is all. Of course, regulating d_0, according to calculation rules, it is possible to reach output beam parameters (waists or waist
positions) for any variable objective. With reference to concrete 12
applications, all of these points are capable of having practical significance.

V. CONCLUSION

1. Design methods for resonation cavities or resonators with self-consistent beam parameters are also appropriate for use in situations where b_i and l_i are not symmetrical.

2. The pliable or flexible cavities which this article sets up thoroughly overcome output saturation and quenching phenomena caused by thermal media lens effects. In this sense, it is possible to say that this thermal lens effect deficiency associated with rod form media has already been eliminated from recurring. As a result of this, this type of pliable or flexible cavity of ours is not only a type of (compensation) method, it is also a type of concept.

3. As far as our thermally stable, pliable or flexible cavities are concerned, they simultaneously possess invariable output beam parameters and full power characteristics.

4. This article, in its basic nature, is large mode volume TEM_{00} design. As a result of this, there is a possibility of obtaining high power, high beam quality outputs.

5. As far as the design methods and compensation principles which have been given are concerned, in principle, they are also appropriate for use with high power gas lasers possessing lens like media effects.

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Li Shichen. Male. Born 1935. Professor. Specialized in optical electronics technology. Has laid special emphasis on the management of research work in the area of optical pulse technology.

CALCULATION OF INTRA-BEAM PERSONNEL LASER EXPOSURE

Xu Guidao

The results of comparisons between experimentally measured safety values for outdoor lasers and theoretically calculated values clearly show that the measured values are higher than the calculated values. It is recognized that in evaluating the safety of multiple mode lasers, the use of general calculations is dangerous.

The use of laser equipment outdoors, over long ranges is increasing everyday. Examples would be laser rangefinders, laser pollution measurements, laser communications, as well as various types of military training laser simulation devices, and so on. In order to assure the safety of personnel during operations, it is necessary to understand the status of the distribution of the amounts of irradiation or the degrees of irradiation of lasers in space. This is particularly the case with the status of the distribution of laser paths. Normally, in laser safety standards, as well as the related references, one often sees calculation formulae associated with amounts of irradiation, degrees of irradiation, and distances. When solving actual problems, these still suffer from certain limitations. This article takes the data measured in our laboratory's laser safety evaluations and discusses calculation problems associated with amounts of irradiation at different distances.

I. COMMONLY USED CALCULATION FORMULAE

The important physical quantities associated with the evaluation of laser safety are the amount of irradiation or degree of irradiation at certain distances. The units are, respectively, J/cm^2 and W/cm^2. In a number of laser safety protection standards, the universally presented calculation formulae are

$$H=\frac{1.27Qe^{-\mu R}}{(a+\varphi R)^2} \quad (1)$$

$$E=\frac{1.27\Phi e^{-\mu R}}{(c+\phi R)^2} \quad (2)$$

In these formulae, H and E are, respectively, the amount of radiation and the degree of radiation at a distance R. Q and Φ are, respectively, the overall amount of output energy and power at the location of the output aperture of the laser equipment. a and ϕ are, respectively, the initial value associated with light beams and the angle of divergence. μ is the coefficient of atmospheric attenuation. The relationships of the various quantities are shown in Fig.1. Formulae (1) and (2) are used, respectively, for calculating the amounts of irradiation for pulse lasers and the degrees or levels of irradiation of continuous lasers. Since the derivations and utilizations are all similar, we will now take formula (1) to be an example and carry out a derivation and discussion.

The definition of the amount of irradiation is the laser energy on a unit surface area. From Fig.1, it is possible to know that, at a location at a distance R, the light striation or spot surfaces approach being

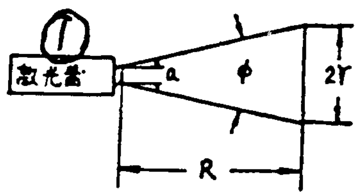


图1 a, φ, r及R关系图

$$\pi r^2 = \pi\left(\frac{a+\phi R}{2}\right)^2$$

Fig.1 A Diagram of the Relationships of a, Φ, r, and R (1) Laser

Considering atmospheric attenuation, the laser energy at location R is:

$$Q' = Qe^{-\mu R}$$

By contrast, at location R, the amount of irradiation is

$$H = \frac{Qe^{-\sigma R}}{\pi\left(\frac{a+\phi R}{2}\right)^2} = \frac{1.27Qe^{-\sigma R}}{(a+\phi R)^2}$$

From the derivations, it is possible to see that the formulae are only appropriate for use with laser distributions of uniform strength, with light beams that do not have large angles of divergence, and for calculations of amounts of irradiation when the atmosphere is not turbulent. In a number of protective standards and protective handbooks, the strengths have been adjusted in the formulae to make them appropriate for use only with light strengths in single mode light beams which present a Gaussian distribution. However, many of the outputs from laser devices are non-single mode light beams, and their strengths most certainly do not present Gaussian distributions. However, in references inside China and outside, there are a number of writers who still ignore the usage conditions of the formulae. An example is the formula given below from reference[1]: 14

$$R = \left[\left(\frac{Q \cdot CF}{\pi/4 \cdot H \cdot P_{Rf}}\right)^{1/2} - a\right] / \phi \qquad (3)$$

In this equation, CF and P_{Rf} are, respectively, the wavelength and repetition rate correction parameters. The other parameters are the same as in equation (1). The author points out that this equation is appropriate for use with any wavelength and any repetition rate associated with safety and protection calculations. It is not difficult to see that equation (3) is derived from equation (1), ignoring atmospheric attenuation, and with the addition of corrections for wavelength and repetition rates. Since it comes from equation (1), it should obey the utilization conditions of equation (1). From the discussion below, one will see that the utilization of equation (1) without the addition of limitations is very dangerous for the carrying out of safety evaluations.

II. PRACTICAL CALCULATION METHODS

As far as safety evaluations of lasers are concerned, they are

principally to solve for the amounts of irradiation associated with light beams at different distances from laser equipment, to be used in order to estimate the possibility of situations which will give rise to injuries in people's eyes, or, alternatively, to solve for the distances at which one has the existence of a specially specified amount of irradiation, in order to precisely determine safety boundaries. With what has been said above, as far as calculations associated with the two types of single and multiple transverse mode light beams are concerned, they should be different.

1. Calculations Dealing With Single Mode Light Beams

As far as the calculation of amounts of irradiation associated with single mode light beams at various distances is concerned, it is possible to directly make use of equation (1). If one solves for the distance at which a certain amount of irradiation exists, because, in both the indices of equation (1) and square quantities, one finds contained the distance R, it is not easy to separate them, and they are difficult to use. We carried this out by handling them as follows. One takes equation (1) index quantities and expands them. making selections to square quantities. One substitutes into equation (1), solves for R, and obtains the equation below.

$$R=\frac{(B-4AC)^{1/2}-B}{2A} \qquad (4)$$

In this,

$$A=\phi^2H-0.64Q\mu^2$$
$$B=a\phi H-1.27Q\mu$$
$$C=a^2H-1.27Q$$

The remainder of the symbols are the same as those in equation (1). If one takes H and substitutes into the safety standards the maximum permissible amounts of irradiation (MPE), and, in conjunction with that, according to the requirements in the standards, applies additional corrections to wavelengths and rates of repetition, then, it is possible to solve for safe distances.

2. Calculations Dealing With Non-Single Mode Light Beams

As far as commonly used laser devices are concerned, in particular, solid state laser devices, quite a large portion of outputs are multiple mode. In the light beams, strength distributions are extremely uneven. Normally, as far as energy concentration points, called "thermal or heat points", are concerned, these thermal points are in states of constant flux and transformation. It is not possible to do calculations from a unified formula. Because of this, we opt for the use of methods involving actual measurments as well as the drawing up of formulae, in order to resolve the problems of safety evaluations associated with laser operating equipment outdoors.

As far as measuring instruments are concerned, we opt for the use of the domestically produced NJ-J1 Model and the U.S. produced RJ-7200 Model energy meters. Before the measurements, they all went through standardization by the National Institute of Measures, and the measurements were all carried out outdoors. The method was as follows. At a certain distance, the energy meters were used to scan back and forth in the light beams from top to bottom and from left to right, in order to precisely fix and measure the amounts of irradiation at the strongest "hot spots", taking the amount of irradiation associated with the data from this spot as representative of the distance in question. In this way, point by point, amounts of irradiation were measured out for different distances. Taking these actually measured data as the basis, through computers, we drew up and solved optimum calculation formulae.

This article collects actual measurements from six pieces of laser equipment, draws up formulae, and calculates data. In conjunction with this, it carries out comparisons with the results which were calculated by the use of the theoretical formula (1).

Table 1 comes from actually measured data. One takes the square sum and relevent coefficients of residual errors associated with data in processing to be reference values. Going through computers, among 20 mathematical models, automatic selection is done of the optimum mathematical models as well as constants for the drawing up. In formulae, R and H quantity grids are, respectively, m and mJ/cm^2.

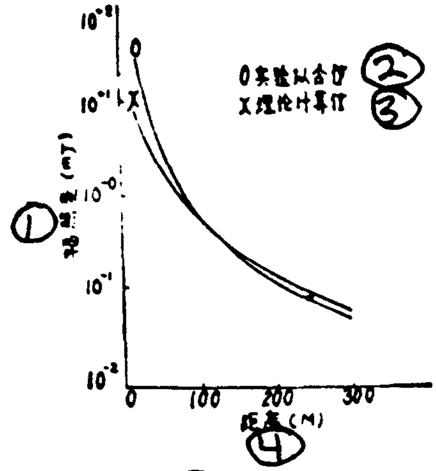
测距机编号 (1)	拟合公式 (2)	常数A值 (3)	常数B值 (4)	常数C值 (5)
1	$H = AR^B$	22150.75	-2.277	
2	$H = AR^B$	2585.503	-1.768	
3	$H = Ae^{BR}$	27.956	-0.0177	
4	$H = C/(1 + AR^B)$	2.435E-7	3.418	14.457
5	$H = Ae^{B/R+C}$	2.919E-3	668.145	88.976
6	$H = Ae^{BR}$	5.957	-0.0207	

Table 1 Optimum Formulae Drawn Up and Constant Values (1) Serial No. of Distance Measuring Device (2) Formulae Drawn Up (3) Values for Constant A (4) Values for Constant B (5) Values for Constant C

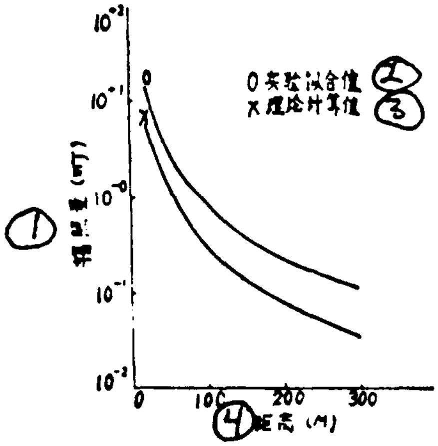
From the drawn up formulae, it is possible to calculate out the amounts of irradiation at various distances. If one takes the maximum permissible amount or exposure (MPE) in the laser safety standards and substitutes into formulae, the corresponding distances R which are obtained are then the safety boundaries. When we are making an evaluation of the safety of laser distance measuring devices or rangefinders, in all cases, use is made of damage or injury effects on animals in order to carry out experimental verification, so as to absolutely guarantee safety in the utilization of laser equipment.

测距机编号 (1)	总输出能量 (2) Q (mJ)	初始束径 (3) a (cm)	发散角 (4) φ (rad)	大气衰减系数 (5) μ (1/M)
1	53	1	1.0E-3	1.2E-4
2	166	1.2	2.4E-3	1.2E-4
3	105	1.6	2.0E-3	1.2E-4
4	109.5	1.6	2.0E-3	1.2E-4
5	7.29	2.2	1.2E-3	1.2E-4
6	9.79	1.1	1.5E-3	1.2E-4

Table 2 Parameters Related to Distance Measuring Devices and Theoretical Calculations (1) Serial No. of the Distance Measuring Device (2) Overall Output Energy (3) Initial Beam Diameter (4) Divergence Angle (5) Atmospheric Attenuation Coefficient



5 图 2



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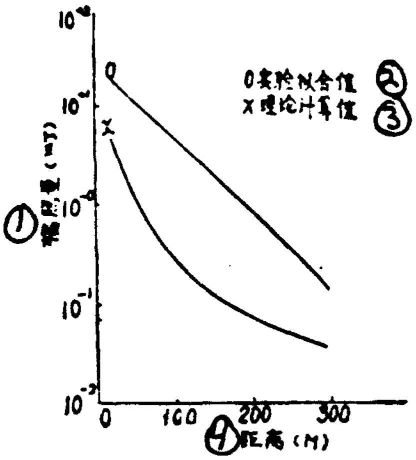
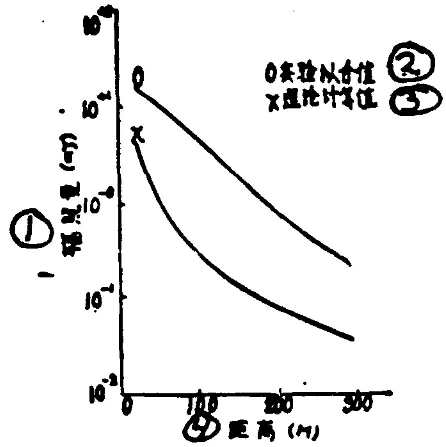
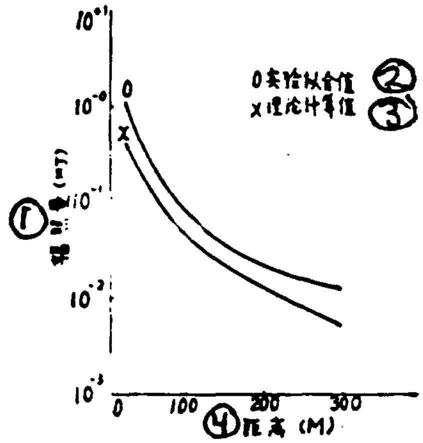


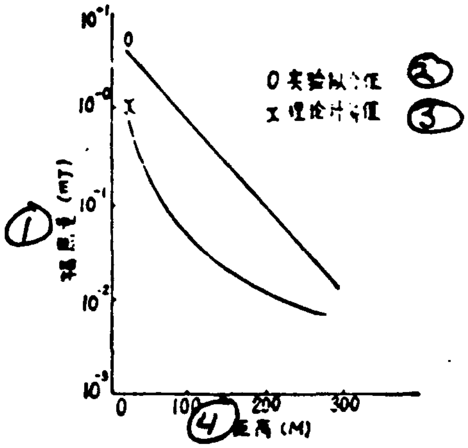
5 图 4



5 图 5



5 图 6



5 图 7

(1) Amount of Irradiation (2) Experimentally Drawn Up Values (3) Theoretically Calculated Values (4) Distance (5) Fig.

Table 2 is the related parameters which are required when carrying out theoretical calculations associated with the various distance measuring devices or rangefinders. As far as the atmospheric attenuation coefficient μ is concerned, it is selected as a numerical value under standard atmospheric visibility.

Making use of the formulae drawn up in Table 1 and the .theoretical calculation formula (1), the amounts of irradiation which are calculated out for the various distances are compared to Fig.2 - Fig.7.

III. DISCUSSION

As far as the calculation of amounts of irradiation associated with long range beam interiors is concerned, it is necessary to consider the effects of light beam modes as well as non-uniform atmospherics. This article primarily discusses the influences of modes or modalities on calculations.

From Fig.2-Fig.7 it is possible to see that, except for the long distances of Fig.2, the actually measured values, in all cases, were higher than the theoretically calculated values. From the trends of the curves, it is possible to divide them into two types. One type is exemplified by Fig.2, 3, and Fig.6. Actually measured values and calculations show trends which are basically in line with each other. The explanation is that, inside light beams, "hot spots" radiate toward the outside with patterns of divergence similar to those of the light beam as a whole. The other type is exemplified by Fig.4, 5, and Fig.7. Actual measurements and theoretically calculated values show relatively great differences between themselves. The special point here is that actually measured values, on semi-logrithmic paper, appropximate being a straight line. At medium distances, the differences between the two values are relatively great. Due to the fact that, at relatively great distances, calculated values drop relatively slowly, the two lines have a tendency to intersect.

With regard to laser safety evaluations, it is necessary to consider the point with the highest amount of irradiation in the radiation field. The data which this article measured is the amount of irradiation on the "hot spots" in light beams. Therefore, it will generally be higher than the theoretically calculated values. From

the Fig., it is possible to see that, at certain distances, there are orders of magnitude of difference. We know that, as far as the drafting up of laser safety standards is concerned, generally 50% of the amounts of irradiation the rates of which produce eye damage (that is, ED_{50}--what is called the damage or injury threshold value) is the basis. Normally, one divides the safety coefficient by 5-20 to obtain the maximum permissible amount of irradiation or exposure (MPE). However, as far as the comparison of amounts of irradiation associated with ED_{50} with the rate of damage or injury occurence being 1% (that is, ED_1) is concerned, our experiments were approximately 1:6-7. It is possible to see the difference between ED_1 amounts of irradiation and MPE. There is only approximately one order of magnitude. Moreover, from Fig.4. 5, and Fig. 7, it is possible to see that, at these certain distances, the values which were actually measured were 14-17 times the calculated values. Therefore, making use of general calculations in order to precisely specify safe distances, with the existence of a certain probability of damage or harm, is very dangerous.

The experiments were carried out outdoors. The effects of weather and other similar conditions on the results of the measurements and tests still require further research.

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